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SBA parameters for DLAP and fused silica, measured at 1053 nm and scaled to 351 nm. Intensity-length products at SBS threshold for transverse or back-reflected scattering

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SUBJECT: SBS parameters for DLAP and fused silica, measured at 1053 nm and scaled to 351 nm. Intensity-length products at SBS threshold for transverse or back-reflected scattering.

1. Introduction

The accurate characterization of both stimulated Brillouin scattering and its prevention through use of increased lasing bandwidth is of fundamental interest in LMF systems.[1] I recently measured at 1053 nm the acoustic lifetime and steady-state SBS gain coefficient for DLAP and fused silica. Measurement of these parameters in KD*P and KDP was attempted, but samples prepared for these experiments damaged at an input intensity below the threshold for stimulated scattering.

The SBS parameters measured at 1053 nm have been scaled to 351 nm, and for both silica and DLAP, the intensity-length products corresponding to threshold for backreflected and transverse SBS have been calculated using a well known model.[2] For fluences of a few J/cm^2 at 351 nm, the calculations for silica describe NOVA experimental results. Threshold gain lengths in DLAP at 351 nm are quite small. While it is now generally believed that suppression of SBS through addition of bandwidth will be required in an LMF, calculations presented here suggest that such suppression might also be required in experiments such as subaperture testing by NOVA of components developed for an LMF.

2. Procedure used at 1053 nm to measure SBS parameters

In these experiments, laser pulses were focused through samples with length greater than 5 cm, and the energy in the backreflected SBS pulse was measured as a function of the energy in the input pulse. Extrapolating this data to a zero value for the reflected energy identified an input energy that was defined to be the threshold energy for SBS. The thresholds were measured for laser pulses with rectangular temporal waveforms and durations of 6, 13, 40, and 70 ns. Corresponding thresholds were also measured for a standard material, compressed methane.

For each material, a value of the acoustic relaxation time, t_b, was determined by fitting an equation for the transient gain coefficient[2] to the observed variation of SBS threshold with pulse duration, t_p. The math is shown in the final section of this note. Once t_b for a material was known, the steady-state gain coefficient, g_b, could be determined relative to g_b of the reference, methane, by again using the gain equation. Data for methane were taken from the paper by Ragulskii.[3]

Since this is not the usual technique for measuring either t_b or g_b, a few additional features of the experiments should be noted. SBS thresholds measured with a focused beam are independent of the focal length of the lens, and the length of the sample is not a critical issue because the majority of the gain occurs in the volume extending a few Rayleigh ranges on either side of the beam waist. In these experiments the focal length was 30 cm, the input beam diameter was 1.4 cm, the Rayleigh range was 0.3 cm, and the beam waist was positioned 2 cm inside the front surface of the sample. For the fused silica sample, I verified that the threshold was not changed by moving the waist to a position 10 cm inside the surface.

Measurements of SBS thresholds are sensitive to phase error on the probe laser beam, and therefore to optical nonuniformity in the test sample. However, use of a relative measurement largely eliminated any impact due to beam parameters, and use of a focused-beam geometry minimized the impact of sample nonuniformity.

3. 1053 nm results

Values measured at 1053 nm for g_b and t_b are given in Table 1. The value for t_b may be slightly model dependent, but the uncertainty in its measurement should be less than 5% since it depends only on the relative accuracy of the thresholds measured for different pulse durations. The uncertainty in the measurement of g_b is probably about 15%, and much of this is the uncertainty in the standard.

Comparison of this data with previous results for fused silica requires scaling to 1053 nm of measurements made at other wavelengths. The first-order assumptions are that t_b scales as wavelength squared, and that g_b scales as the seventh power of refractive index.[1]

A single value of the acoustic lifetime for silica, 1 ns, was measured in both the 488 nm experiments of Schroeder, et al.[4] and the recent 532 nm experiments that were done at Stanford under contract to LLNL. Because the wavelengths are different, scaling this single value to 1053 nm produces two values, 4.0 and 4.7 ns, that can be compared to my result, t_b = 3.9 ns. For DLAP, the 532-nm lifetime measured at Stanford, t_b = 1.7, scales to 6.7 ns at 1053 nm, whereas I have measured t_b = 5.5 ns.

Several values of g_b in silica have been reported. At 488 nm, $g_b = 4.8 \times 10^{-9}$ cm/W was measured by Schroeder, et al.[4] Ippen and Stolen measured a value of 4.3×10^{-9} in their study at 535 nm of scattering in fibers, and for that wavelength calculated a value of 5.8×10^{-9} from an expression that involves measured values of several parameters.[5] Using tabulated values of the refractive index and the previously stated scaling rule, we find that the corresponding values at 1053 nm are 4.5, 4.1, and 5.5×10^{-9}. The result of my experiment, 4.8×10^{-9}, is in reasonable agreement with all of these data, and perhaps coincidentally, is almost exactly equal to their average value.

I am not aware of other finished measurements of g_b in DLAP, although Stanford is working on this problem. Their preliminary measurements at 532 nm found g_b for DLAP to be about 10 times that of silica, whereas the current 1053 nm data suggests that ratio is approximately 4. Clearly, we should let them finish before worrying about this difference, but even the smaller gain determined from my data is large enough to pose a serious problem.

The sample of KD*P damaged at an input energy below the SBS threshold for DLAP, and we believe that its SBS threshold should be larger than that of DLAP, so this result probably does not have significant meaning. In contrast, the samples of KDP damaged only at input energies 1.3-1.5 times larger than the SBS threshold for silica, whereas we expected that the SBS threshold in KDP would be comparable to or smaller than that of silica. It is possible that the rather large absorption in KDP interfered with excitation of SBS, although estimates made through equations provided by Kaiser and Maier[2] and by Bubis, et al.[6] indicate that absorption greater than 0.1 cm^{-1} would be required. Therefore, we need to understand the interaction of absorption and SBS, since absorption is in general larger in the UV where SBS poses the greatest threat.

4. Gain length at SBS threshold

Using Eq. 3 from the final section, I calculated for DLAP and silica, at both 1053 nm and 351 nm, the gain length, L_t, that is necessary for excitation of either backreflected or transverse SBS by a plane-wave beam that delivers fluence F_p. SBS parameters for 351 nm were obtained by scaling of recent 1053-nm data. The waveform of the pulse was assumed to be rectangular. For $t_p \gg t_b$, L_t exhibits an obvious dependence on pulse duration, and threshold gain lengths were calculated for pulse durations of 2, 5 and 10 ns. For $t_p \lesssim t_b$, L_t is essentially independent of pulse duration, and the calculation was made only for t_p = 5 ns. Results are shown in the attached figures.

For transverse scattering, L_t is a distance measured along a coordinate that is perpendicular to the direction of propagation for the assumed plane-wave irradiation. The maximum possible value for L_t is the distance ct_p/n that the scattered light can propagate during time t_p in a medium with refractive index n. Values larger than this maximum are predicted by Eq. 3 for small values of F_p; these have no physical meaning and should be ignored. Dashed lines in Figs. 1 and 2 indicate maximum values of L_t for t_p equal 2, 5, and 10 ns.

For backscattering, L_t is a thickness measured along the direction of beam propagation. It is the summed thickness of all components made of a single material and contained within a beam segment with length not exceeding $ct_p/2n$ which is onehalf the physical length of the laser pulse. Larger values displayed in Figs. 1 and 2 for small values of F_p must be ignored.

Since the equation used in calculation of L_t was derived from a classical model that assumed single values for the frequencies of both the input and scattered waves, the results are at best accurate only for narrow input bandwidth. However, for silica, the calculations agree rather well with Nova results.

As an example, consider the modeling of the very nice piece of data given in Fig. 5 in the paper by John Murray, et al.[1] A 2.4 ns, 351 nm pulse delivered a fluence of 1.75 J/cm^2 to a silica window. Waveforms were recorded for both the pulse transmitted through the window and the transversely scattered pulse. Observable increase in the scattered signal began at about 1.4-1.5 ns into the pulse, and for these values of pulse duration, the maximum possible gain lengths are 29-31 cm. Spatial or temporal variations of either phase or bandwidth could have caused the effective gain length to be shorter, but such effects are probably negligible for a beam of Nova. From Eq. 3 below, L_t for transverse scattering in silica is 28 cm for a 1.4-ns pulse at 1.02 J/cm^2, and 26 cm for a 1.5 ns pulse at 1.09 j/cm^2. The stated fluences are the fractions of the total fluence that delivered in times of 1.4 and 1.5 ns. For either choice of the time of initiation of scattering, calculated and probable values of L_t agree to within the uncertainty in SBS parameters.

The agreement in calculated and experimental values for silica suggests that the simple model might also provide reasonable values of L_t for DLAP. For backscattering at 1053 nm , calculated values of L_t in DLAP range from 15 cm at 5 J/cm^2 to 3.6 cm at 20 J/cm^2, and are about 38% of corresponding values in silica. For transverse scattering, L_t is larger by a factor of about 1.4. Therefore, stimulated scattering will be observed in DLAP during 1053-nm damage testing at 20 j/cm^2 if the diameter of the beam is greater than 5 cm.

At 351 nm, for pulses with duration of 2, 5 or 10 ns, values of L_t for DLAP are smaller by a factor of, respectively, 12, 8 or 6 than corresponding values at 1053 nm. SBS should be excited during typical 351 nm damage experiments at fluences of 10-20 J/cm^2 in DLAP crystals with either thickness or diameter greater than a few millimeters, and use of DLAP in a large, high-fluence laser will be difficult. There are three caveats: (1) if the Stanford data is correct, values of L_t are smaller than those plotted in attached figures, (2) absorption at 351 nm might increase L_t, (3) it might be possible to suppress SBS in DLAP through addition of bandwidth.

4. Math

The concept of a "threshold" in stimulated scattering is a bit nebulous. In stimulated Brillouin scattering, the presence of an intense electromagnetic wave in a transparent medium "stimulates" or creates an acoustic wave that is capable of reflecting a large fraction of the input intensity. During the growth of the acoustic wave, the intensity of the scattered light increases exponentially. The process is much like the initiation of lasing in an oscillator, except that the stored energy is in the input field instead of being in an excited state of a lasing medium. If the input field is of adequate intensity and duration, the "threshold" for stimulated scattering will be exceeded and intense scattering will be observed. In a laser, threshold-level pumping produces a roundtrip gain that equals the roundtrip loss. Such a neat calibrating condition does not exist for stimulated scattering, so it is conventional to define threshold as creation of a scattered intensity that is 1-10% of the input intensity. In practice, measurement of an SBS threshold through use of the extrapolation of data that was described in Section 2 removes most of the ambiguity, and identifies a threshold that corresponds to SBS reflectance of less than 1%.

Light spontaneously scattered from existing acoustic fluctuations into a beam of small solid angle must be amplified by a factor of exp(25-30) to produce an SBS beam at threshold intensity. When this amplification occurs during pumping by a pulse with $t_p \lesssim 15t_b$, growth in the intensity of the scattered wave is described by the transient-gain coefficient, A. An equation for this coefficient given by Kaiser and Maier,[2] and the choice A = 30, provided an adequate representation of the SBS thresholds measured during study of phase conjugation. For a pulse with temporally rectangular waveform propagating along the z axis,

$$A = -\frac{t_p}{t_b} + \left(\frac{4g_b t_p}{t_b} \int I \, dz\right)^{1/2} = 30 \qquad (1)$$

where the integral is over the length of the gain volume. Inverting the equation provides a relationship between the SBS parameters and the duration and intensity of the threshold-level pump pulse.

$$\int I \, dz = \frac{t_b}{4g_b t_p}\left(30 + \frac{t_p}{t_b}\right)^2 \qquad (2)$$

When the pump pulse is a plane wave, the intensity is spatially constant and equal to the integrated fluence, F_p, divided by the pulse duration. Solving the trivial integral provides an expression for the threshold path length, L_t, as a function of F_p.

$$L_t = \frac{t_b}{4g_b F_p}\left(30 + \frac{t_p}{t_b}\right)^2 \qquad (3)$$

The degree of transiency is determined by the relative magnitudes of the ratio t_p/t_b and the constant, 30. For extreme transiency, the ratio can be neglected, and L_t depends only on the fluence in the incident pulse. Including the ratio maintains a dependence on both F_p and t_p, and therefore intensity, and automatically provides a bridge between extreme transiency and the steady state.

Equation 3, with correct values for g_b and t_b, models either transverse scattering in beams such as those of Nova or backreflection induced with a collimated beam.

To model thresholds for backreflected SBS in a focused-beam experiment, it is convenient to have an expression that relates the input pulse energy, E_p, to the SBS parameters. For a focused beam propagating on the z axis, the intensity can be written as a product of the total input power, P, and a function, f(x,y,z), that describes the distribution of power in the focused beam. Recognizing that $P = E_p/t_p$ for a rectangular pulse, we obtain

$$E_p \int f(x,y,z)\, dz = \frac{t_b}{4g_b}\left(30 + \frac{t_p}{t_b}\right)^2 \qquad (4)$$

The gain varies with transverse coordinates, being for example, greatest on axis for a Gaussian beam, but at all points across the beam, the gain is directly related to E_p. If threshold is measured at several values of t_p without changing the focusing, the integral is the same for all these measurements although its value is not known. Fitting the threshold energies to Eq. 4 then provides a measure of t_b. Similarly, the relative values of g_b for two media can be determined if t_b is known for both media.

The values of g_b and t_b measured by observing backreflection are correct only for scattering at an angle of 180°. For scattering at other angles, the equations remain the same, but different values of t_b and g_b must be used. g_b varies as $(\sin \theta/2)^{-1}$, and at 90° is larger by a factor of 1.4 than at 180°. t_b varies as $(\sin \theta/2)^{-2}$, and is therefore larger by a factor of 2 at 90°.

For transient scattering, the variation of L_t with θ is determined primarily by the ratio t_b / g_b, and L_t varies as $(\sin \theta/2)^{-1}$. A more precise equation is produced simply by plugging the angular dependence into Eq. 3.

5. Acknowledgments

Discussions with John Murray concerning the merits of various methods of calculating transverse gain lengths, assistance by Camille Bibeau in generation of the attached graphs, and maintenance of the laser by Gary Ullery are gratefully acknowledged.

6. References

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Table 1. Steady-state gain coefficients and acoustic lifetimes for DLAP and silica. Units are cm/W for g_b and ns for t_b. Values for 1053 nm and θ = 180° were measured. Remaining parameters were computed using scaling laws described in the text.

	Silica (1053 nm)	Silica (351 nm)	DLAP (1053 nm)	DLAP 351 nm)
$g_b(\theta=180°)$	4.8×10^{-9}	5.4×10^{-9}	18×10^{-9}	22×10^{-9}
$g_b(\theta=90°)$	6.8×10^{-9}	7.6×10^{-9}	26×10^{-9}	31×10^{-9}
$t_b(\theta=180°)$	3.9	0.43	5.5	0.61
$t_b(\theta=90°)$	7.8	0.86	11	1.2

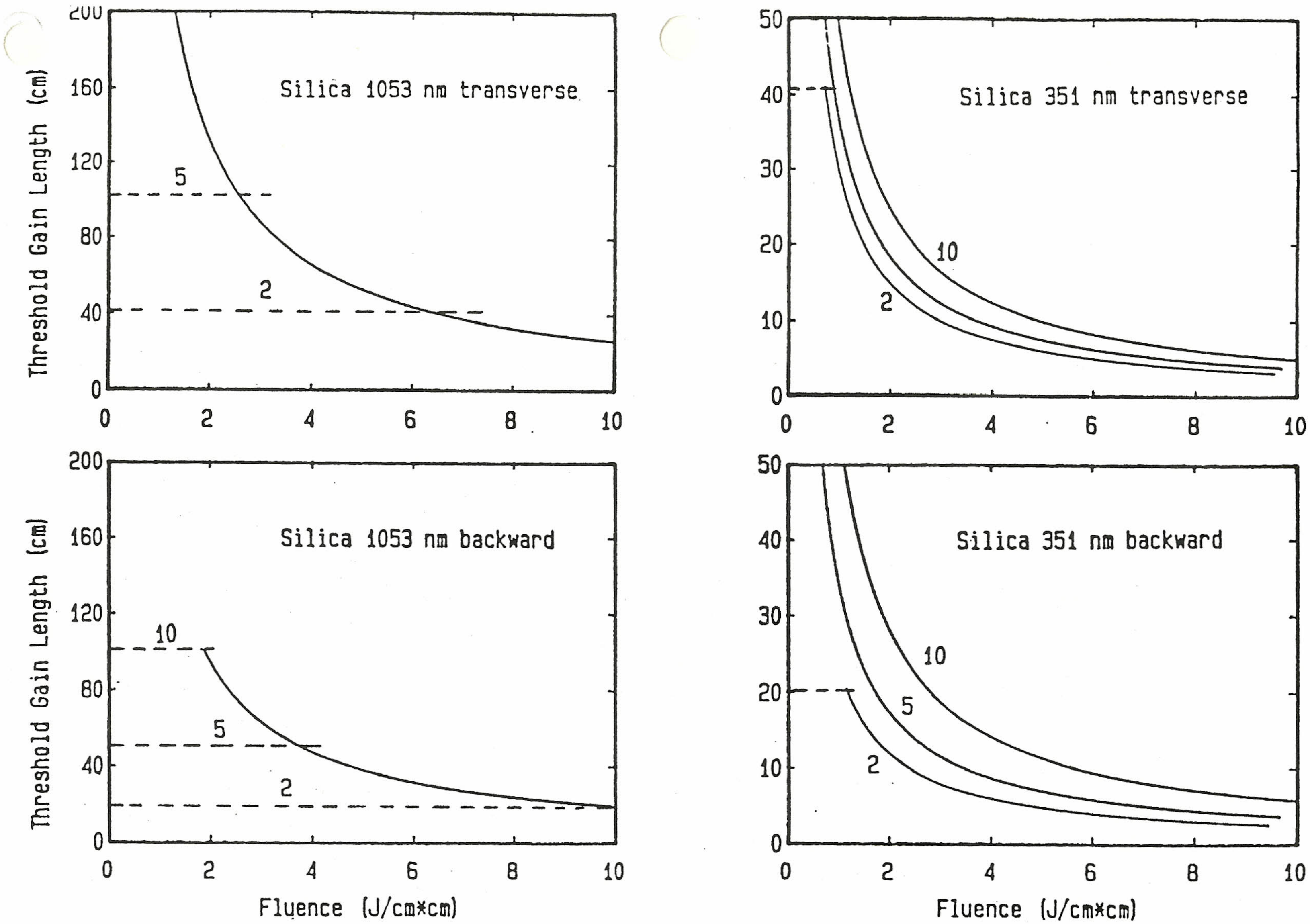

Fig. 1. Left side: Threshold gain length, L_t, at 1053 nm in silica vs. pulse fluence, F_p. The solid line represents L_t for pulse durations betweew 2 and 10 ns, but the limit of applicability, $L_t < ct_p/n$, varies with pulse duration as indicated by the dashed lines. Right side: L_t vs. F_p at 351 nm for t_p of 2, 5 and 10 ns, with indicated limits of applicability.

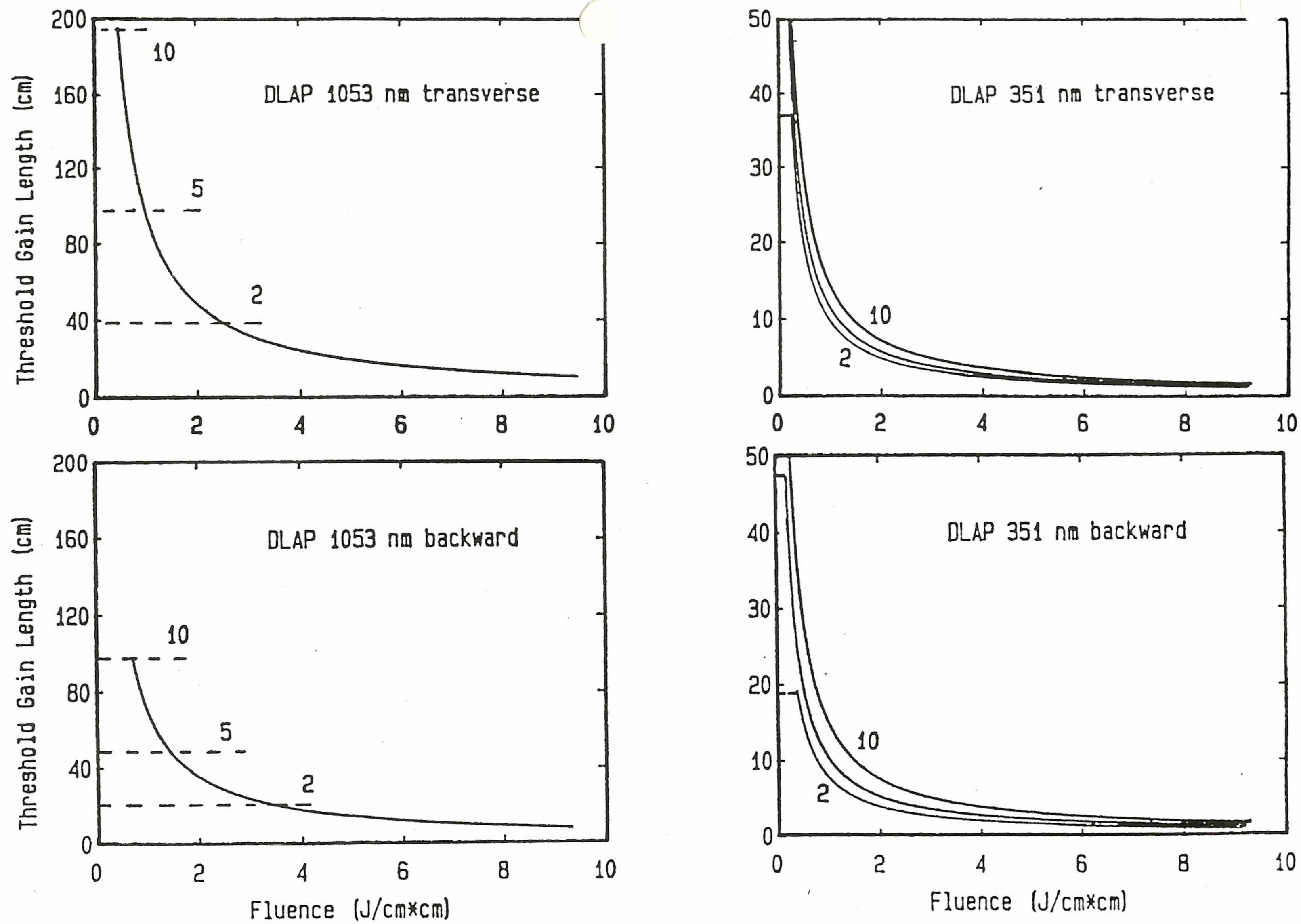

Fig. 2. Left side: Threshold gain length, L_t, at 1053 nm in DLAP vs. pulse fluence, F_p. The solid curve represents L_t for pulse durations between 2 and 10 ns, but the limit of applicability, $L_t < ct_p/n$, varies with pulse duration as indicated by the dashed lines. Right side: L_t vs. F_p at 351 nm for t_p of 2, 5 and 10 ns, with indicated limits of applicability.

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